

Measurement of the $D^*(2010)^+$ Meson Width and the $D^*(2010)^+ - D^0$ Mass Difference

J. P. Lees,¹ V. Poireau,¹ V. Tisserand,¹ E. Grauges,² A. Palano,^{3,4} G. Eigen,⁵ B. Stugu,⁵ D. N. Brown,⁶ L. T. Kerth,⁶ Yu. G. Kolomensky,⁶ M. J. Lee,⁶ G. Lynch,⁶ H. Koch,⁷ T. Schroeder,⁷ C. Hearty,⁸ T. S. Mattison,⁸ J. A. McKenna,⁸ R. Y. So,⁸ A. Khan,⁹ V. E. Blinov,^{10,12} A. R. Buzykaev,¹⁰ V. P. Druzhinin,^{10,11} V. B. Golubev,^{10,11} E. A. Kravchenko,^{10,11} A. P. Onuchin,^{10,12} S. I. Serebnyakov,^{10,11} Yu. I. Skovpen,^{10,11} E. P. Solodov,^{10,11} K. Yu. Todyshev,^{10,11} A. N. Yushkov,¹⁰ D. Kirkby,¹³ A. J. Lankford,¹³ M. Mandelkern,¹³ B. Dey,¹⁴ J. W. Gary,¹⁴ O. Long,¹⁴ G. M. Vitug,¹⁴ C. Campagnari,¹⁵ M. Franco Sevilla,¹⁵ T. M. Hong,¹⁵ D. Kovalskyi,¹⁵ J. D. Richman,¹⁵ C. A. West,¹⁵ A. M. Eisner,¹⁶ W. S. Lockman,¹⁶ A. J. Martinez,¹⁶ B. A. Schumm,¹⁶ A. Seiden,¹⁶ D. S. Chao,¹⁷ C. H. Cheng,¹⁷ B. Echenard,¹⁷ K. T. Flood,¹⁷ D. G. Hitlin,¹⁷ P. Ongmongkolkul,¹⁷ F. C. Porter,¹⁷ R. Andreassen,¹⁸ C. Fabbry,¹⁸ Z. Huard,¹⁸ B. T. Meadows,¹⁸ M. D. Sokoloff,¹⁸ L. Sun,¹⁸ P. C. Bloom,¹⁹ W. T. Ford,¹⁹ A. Gaz,¹⁹ U. Nauenberg,¹⁹ J. G. Smith,¹⁹ S. R. Wagner,¹⁹ R. Ayad,^{20,*} W. H. Toki,²⁰ B. Spaan,²¹ K. R. Schubert,²² R. Schwierz,²² D. Bernard,²³ M. Verderi,²³ S. Playfer,²⁴ D. Bettoni,²⁵ C. Bozzi,²⁵ R. Calabrese,^{25,26} G. Cibinetto,^{25,26} E. Fioravanti,^{25,26} I. Garzia,^{25,26} E. Luppi,^{25,26} L. Piemontese,²⁵ V. Santoro,²⁵ R. Baldini-Ferroli,²⁷ A. Calcaterra,²⁷ R. de Sangro,²⁷ G. Finocchiaro,²⁷ S. Martellotti,²⁷ P. Patteri,²⁷ I. M. Peruzzi,^{27,*} M. Piccolo,²⁷ M. Rama,²⁷ A. Zallo,²⁷ R. Contri,^{28,29} E. Guido,^{28,29} M. Lo Vetere,^{28,29} M. R. Monge,^{28,29} S. Passaggio,²⁸ C. Patrignani,^{28,29} E. Robutti,²⁸ B. Bhuyan,³⁰ V. Prasad,³⁰ M. Morii,³¹ A. Adametz,³² U. Uwer,³² H. M. Lacker,³³ P. D. Dauncey,³⁴ U. Mallik,³⁵ C. Chen,³⁶ J. Cochran,³⁶ W. T. Meyer,³⁶ S. Prell,³⁶ A. E. Rubin,³⁶ A. V. Gritsan,³⁷ N. Arnaud,³⁸ M. Davier,³⁸ D. Derkach,³⁸ G. Grosdidier,³⁸ F. Le Diberder,³⁸ A. M. Lutz,³⁸ B. Malaescu,³⁸ P. Roudeau,³⁸ A. Stocchi,³⁸ G. Wormser,³⁸ D. J. Lange,³⁹ D. M. Wright,³⁹ J. P. Coleman,⁴⁰ J. R. Fry,⁴⁰ E. Gabathuler,⁴⁰ D. E. Hutchcroft,⁴⁰ D. J. Payne,⁴⁰ C. Touramanis,⁴⁰ A. J. Bevan,⁴¹ F. Di Lodovico,⁴¹ R. Sacco,⁴¹ G. Cowan,⁴² J. Bougher,⁴³ D. N. Brown,⁴³ C. L. Davis,⁴³ A. G. Denig,⁴⁴ M. Fritsch,⁴⁴ W. Gradl,⁴⁴ K. Griessinger,⁴⁴ A. Hafner,⁴⁴ E. Prencipe,⁴⁴ R. J. Barlow,^{45,*} G. D. Lafferty,⁴⁵ E. Behn,⁴⁶ R. Cenci,⁴⁶ B. Hamilton,⁴⁶ A. Jawahery,⁴⁶ D. A. Roberts,⁴⁶ R. Cowan,⁴⁷ D. Dujmic,⁴⁷ G. Sciolla,⁴⁷ R. Cheaib,⁴⁸ P. M. Patel,^{48,*} S. H. Robertson,⁴⁸ P. Biassoni,^{49,50} N. Neri,⁴⁹ F. Palombo,^{49,50} L. Cremaldi,⁵¹ R. Godang,^{51,||} P. Sonnek,⁵¹ D. J. Summers,⁵¹ X. Nguyen,⁵² M. Simard,⁵² P. Taras,⁵² G. De Nardo,^{53,54} D. Monorchio,^{53,54} G. Onorato,^{53,54} C. Sciacca,^{53,54} M. Martinelli,⁵⁵ G. Raven,⁵⁵ C. P. Jessop,⁵⁶ J. M. LoSecco,⁵⁶ K. Honscheid,⁵⁷ R. Kass,⁵⁷ J. Brau,⁵⁸ R. Frey,⁵⁸ N. B. Sinev,⁵⁸ D. Strom,⁵⁸ E. Torrence,⁵⁸ E. Feltresi,^{59,60} M. Margoni,^{59,60} M. Morandin,⁵⁹ M. Posocco,⁵⁹ M. Rotondo,⁵⁹ G. Simi,⁵⁹ F. Simonetto,^{59,60} R. Stroili,^{59,60} S. Akar,⁶¹ E. Ben-Haim,⁶¹ M. Bomben,⁶¹ G. R. Bonneaud,⁶¹ H. Briand,⁶¹ G. Calderini,⁶¹ J. Chauveau,⁶¹ Ph. Leruste,⁶¹ G. Marchiori,⁶¹ J. Ocariz,⁶¹ S. Sitt,⁶¹ M. Biasini,^{62,63} E. Manoni,⁶² S. Pacetti,^{62,63} A. Rossi,⁶² C. Angelini,^{64,65} G. Batignani,^{64,65} S. Bettarini,^{64,65} M. Carpinelli,^{64,65,*} G. Casarosa,^{64,65} A. Cervelli,^{64,65} F. Forti,^{64,65} M. A. Giorgi,^{64,65} A. Lusiani,^{64,66} B. Oberhof,^{64,65} E. Paoloni,^{64,65} A. Perez,⁶⁴ G. Rizzo,^{64,65} J. J. Walsh,⁶⁴ D. Lopes Pegna,⁶⁷ J. Olsen,⁶⁷ A. J. S. Smith,⁶⁷ R. Faccini,^{68,69} F. Ferrarotto,⁶⁸ F. Ferroni,^{68,69} M. Gaspero,^{68,69} L. Li Gioi,⁶⁸ G. Piredda,⁶⁸ C. Büniger,⁷⁰ O. Grünberg,⁷⁰ T. Hartmann,⁷⁰ T. Leddig,⁷⁰ C. Voß,⁷⁰ R. Waldi,⁷⁰ T. Adye,⁷¹ E. O. Olaiya,⁷¹ F. F. Wilson,⁷¹ S. Emery,⁷² G. Hamel de Monchenault,⁷² G. Vasseur,⁷² Ch. Yèche,⁷² F. Anulli,⁷³ D. Aston,⁷³ D. J. Bard,⁷³ J. F. Benitez,⁷³ C. Cartaro,⁷³ M. R. Convery,⁷³ J. Dorfan,⁷³ G. P. Dubois-Felsmann,⁷³ W. Dunwoodie,⁷³ M. Ebert,⁷³ R. C. Field,⁷³ B. G. Fulsom,⁷³ A. M. Gabareen,⁷³ M. T. Graham,⁷³ C. Hast,⁷³ W. R. Innes,⁷³ P. Kim,⁷³ M. L. Kocian,⁷³ D. W. G. S. Leith,⁷³ P. Lewis,⁷³ D. Lindemann,⁷³ B. Lindquist,⁷³ S. Luitz,⁷³ V. Luth,⁷³ H. L. Lynch,⁷³ D. B. MacFarlane,⁷³ D. R. Muller,⁷³ H. Neal,⁷³ S. Nelson,⁷³ M. Perl,⁷³ T. Pulliam,⁷³ B. N. Ratcliff,⁷³ A. Roodman,⁷³ A. A. Salnikov,⁷³ R. H. Schindler,⁷³ A. Snyder,⁷³ D. Su,⁷³ M. K. Sullivan,⁷³ J. Va'vra,⁷³ A. P. Wagner,⁷³ W. F. Wang,⁷³ W. J. Wisniewski,⁷³ M. Wittgen,⁷³ D. H. Wright,⁷³ H. W. Wulsin,⁷³ V. Ziegler,⁷³ W. Park,⁷⁴ M. V. Purohit,⁷⁴ R. M. White,^{74,*} J. R. Wilson,⁷⁴ A. Randle-Conde,⁷⁵ S. J. Sekula,⁷⁵ M. Bellis,⁷⁶ P. R. Burchat,⁷⁶ T. S. Miyashita,⁷⁶ E. M. T. Puccio,⁷⁶ M. S. Alam,⁷⁷ J. A. Ernst,⁷⁷ R. Gorodeisky,⁷⁸ N. Guttman,⁷⁸ D. R. Peimer,⁷⁸ A. Soffer,⁷⁸ S. M. Spanier,⁷⁹ J. L. Ritchie,⁸⁰ A. M. Ruland,⁸⁰ R. F. Schwitters,⁸⁰ B. C. Wray,⁸⁰ J. M. Izen,⁸¹ X. C. Lou,⁸¹ F. Bianchi,^{82,83} F. De Mori,^{82,83} A. Filippi,⁸² D. Gamba,^{82,83} S. Zambito,^{82,83} L. Lanceri,^{84,85} L. Vitale,^{84,85} F. Martinez-Vidal,⁸⁶ A. Oyanguren,⁸⁶ P. Villanueva-Perez,⁸⁶ H. Ahmed,⁸⁷ J. Albert,⁸⁷ Sw. Banerjee,⁸⁷ F. U. Bernlochner,⁸⁷ H. H. F. Choi,⁸⁷ G. J. King,⁸⁷ R. Kowalewski,⁸⁷ M. J. Lewczuk,⁸⁷ T. Lueck,⁸⁷ I. M. Nugent,⁸⁷

J. M. Roney,⁸⁷ R. J. Sobie,⁸⁷ N. Tasneem,⁸⁷ T. J. Gershon,⁸⁸ P. F. Harrison,⁸⁸ T. E. Latham,⁸⁸
H. R. Band,⁸⁹ S. Dasu,⁸⁹ Y. Pan,⁸⁹ R. Prepost,⁸⁹ and S. L. Wu⁸⁹

(BABAR Collaboration)

- ¹Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
²Departament ECM, Facultat de Física, Universitat de Barcelona, E-08028 Barcelona, Spain
³INFN Sezione di Bari, I-70126 Bari, Italy
⁴Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
⁵Institute of Physics, University of Bergen, N-5007 Bergen, Norway
⁶Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
⁷Institut für Experimentalphysik I, Ruhr Universität Bochum, D-44780 Bochum, Germany
⁸University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
⁹Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
¹⁰Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090, Russia
¹¹Novosibirsk State University, Novosibirsk 630090, Russia
¹²Novosibirsk State Technical University, Novosibirsk 630092, Russia
¹³University of California at Irvine, Irvine, California 92697, USA
¹⁴University of California at Riverside, Riverside, California 92521, USA
¹⁵University of California at Santa Barbara, Santa Barbara, California 93106, USA
¹⁶Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, California 95064, USA
¹⁷California Institute of Technology, Pasadena, California 91125, USA
¹⁸University of Cincinnati, Cincinnati, Ohio 45221, USA
¹⁹University of Colorado, Boulder, Colorado 80309, USA
²⁰Colorado State University, Fort Collins, Colorado 80523, USA
²¹Fakultät Physik, Technische Universität Dortmund, D-44221 Dortmund, Germany
²²Institut für Kern- und Teilchenphysik, Technische Universität Dresden, D-01062 Dresden, Germany
²³Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France
²⁴University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
²⁵INFN Sezione di Ferrara, I-44122 Ferrara, Italy
²⁶Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, I-44122 Ferrara, Italy
²⁷INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
²⁸INFN Sezione di Genova, I-16146 Genova, Italy
²⁹Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy
³⁰Indian Institute of Technology Guwahati, Guwahati, Assam 781 039, India
³¹Harvard University, Cambridge, Massachusetts 02138, USA
³²Physikalisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany
³³Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
³⁴Imperial College London, London SW7 2AZ, United Kingdom
³⁵University of Iowa, Iowa City, Iowa 52242, USA
³⁶Iowa State University, Ames, Iowa 50011-3160, USA
³⁷Johns Hopkins University, Baltimore, Maryland 21218, USA
³⁸Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, F-91898 Orsay Cedex, France
³⁹Lawrence Livermore National Laboratory, Livermore, California 94550, USA
⁴⁰University of Liverpool, Liverpool L69 7ZE, United Kingdom
⁴¹Queen Mary, University of London, London E1 4NS, United Kingdom
⁴²University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
⁴³University of Louisville, Louisville, Kentucky 40292, USA
⁴⁴Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
⁴⁵University of Manchester, Manchester M13 9PL, United Kingdom
⁴⁶University of Maryland, College Park, Maryland 20742, USA
⁴⁷Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
⁴⁸McGill University, Montréal, Québec, Canada H3A 2T8
⁴⁹INFN Sezione di Milano, I-20133 Milano, Italy
⁵⁰Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
⁵¹University of Mississippi, University, Mississippi 38677, USA
⁵²Physique des Particules, Université de Montréal, Montréal, Québec, Canada H3C 3J7
⁵³INFN Sezione di Napoli, I-80126 Napoli, Italy

⁵⁴*Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy*⁵⁵*NIKHEF, National Institute for Nuclear Physics and High Energy Physics,
NL-1009 DB Amsterdam, Netherlands*⁵⁶*University of Notre Dame, Notre Dame, Indiana 46556, USA*⁵⁷*Ohio State University, Columbus, Ohio 43210, USA*⁵⁸*University of Oregon, Eugene, Oregon 97403, USA*⁵⁹*INFN Sezione di Padova, I-35131 Padova, Italy*⁶⁰*Dipartimento di Fisica, Università di Padova, I-35131 Padova, Italy*⁶¹*Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6,
Université Denis Diderot-Paris7, F-75252 Paris, France*⁶²*INFN Sezione di Perugia, I-06123 Perugia, Italy*⁶³*Dipartimento di Fisica, Università di Perugia, I-06123 Perugia, Italy*⁶⁴*INFN Sezione di Pisa, I-56127 Pisa, Italy*⁶⁵*Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy*⁶⁶*Scuola Normale Superiore di Pisa, I-56127 Pisa, Italy*⁶⁷*Princeton University, Princeton, New Jersey 08544, USA*⁶⁸*INFN Sezione di Roma, I-00185 Roma, Italy*⁶⁹*Dipartimento di Fisica, Università di Roma La Sapienza, I-00185 Roma, Italy*⁷⁰*Universität Rostock, D-18051 Rostock, Germany*⁷¹*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*⁷²*CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France*⁷³*SLAC National Accelerator Laboratory, Stanford, California 94309 USA*⁷⁴*University of South Carolina, Columbia, South Carolina 29208, USA*⁷⁵*Southern Methodist University, Dallas, Texas 75275, USA*⁷⁶*Stanford University, Stanford, California 94305-4060, USA*⁷⁷*State University of New York, Albany, New York 12222, USA*⁷⁸*School of Physics and Astronomy, Tel Aviv University, Tel Aviv, 69978, Israel*⁷⁹*University of Tennessee, Knoxville, Tennessee 37996, USA*⁸⁰*University of Texas at Austin, Austin, Texas 78712, USA*⁸¹*University of Texas at Dallas, Richardson, Texas 75083, USA*⁸²*INFN Sezione di Torino, I-10125 Torino, Italy*⁸³*Dipartimento di Fisica Sperimentale, Università di Torino, I-10125 Torino, Italy*⁸⁴*INFN Sezione di Trieste, I-34127 Trieste, Italy*⁸⁵*Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*⁸⁶*IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain*⁸⁷*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*⁸⁸*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*⁸⁹*University of Wisconsin, Madison, Wisconsin 53706, USA*

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We measure the mass difference Δm_0 between the $D^*(2010)^+$ and the D^0 and the natural linewidth Γ of the transition $D^*(2010)^+ \rightarrow D^0 \pi^+$. The data were recorded with the BABAR detector at center-of-mass energies at and near the $\Upsilon(4S)$ resonance, and correspond to an integrated luminosity of approximately 477 fb^{-1} . The D^0 is reconstructed in the decay modes $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$. For the decay mode $D^0 \rightarrow K^- \pi^+$ we obtain $\Gamma = (83.4 \pm 1.7 \pm 1.5) \text{ keV}$ and $\Delta m_0 = (145425.6 \pm 0.6 \pm 1.8) \text{ keV}$, where the quoted errors are statistical and systematic, respectively. For the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ mode we obtain $\Gamma = (83.2 \pm 1.5 \pm 2.6) \text{ keV}$ and $\Delta m_0 = (145426.6 \pm 0.5 \pm 2.0) \text{ keV}$. The combined measurements yield $\Gamma = (83.3 \pm 1.2 \pm 1.4) \text{ keV}$ and $\Delta m_0 = (145425.9 \pm 0.4 \pm 1.7) \text{ keV}$; the width is a factor of approximately 12 times more precise than the previous value, while the mass difference is a factor of approximately 6 times more precise.

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The linewidth of the $D^*(2010)^+$ (D^{*+}) provides a window into a nonperturbative regime of strong interaction physics where the charm quark is the heavier meson constituent [1–3]. The linewidth provides an experimental test of D meson spectroscopic models, and is related to the strong coupling of the $D^* D \pi$ system $g_{D^* D \pi}$. In the

heavy-quark limit, which is not necessarily a good approximation for the charm quark [4], this coupling can be related to the universal coupling of heavy mesons to a pion \hat{g} . Since the decay $B^* \rightarrow B \pi$ is kinematically forbidden, it is not possible to measure the coupling $g_{B^* B \pi}$ directly. However, the D and B systems can be related through \hat{g} ,

allowing the calculation of $g_{B^*B\pi}$, which is needed for a model-independent extraction of $|V_{ub}|$ [5,6] and which forms one of the larger theoretical uncertainties for the determination of $|V_{ub}|$ [7].

We study the $D^{*+} \rightarrow D^0 \pi^+$ transition, using the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decay modes, to extract values of the D^{*+} width Γ and the difference between the D^{*+} and D^0 masses Δm_0 . Values are reported in natural units and the use of charge conjugate reactions is implied throughout this Letter. The only prior measurement of the width is $\Gamma = (96 \pm 4 \pm 22)$ keV by the CLEO Collaboration, where the uncertainties are statistical and systematic, respectively [8]. In the present analysis, we use a data sample that is approximately 50 times larger. This allows us to apply restrictive selection criteria to reduce background and to investigate sources of systematic uncertainty with high precision.

To extract Γ , we fit the distribution of the mass difference between the reconstructed D^{*+} and the D^0 masses, Δm . The signal component is described with a P -wave relativistic Breit-Wigner (RBW) function convolved with a resolution function based on a GEANT4 Monte Carlo (MC) simulation of the detector response [9].

The FWHM of the RBW line shape (≈ 100 keV) is much less than the FWHM of the almost Gaussian resolution function which describes more than 99% of the signal (≈ 300 keV). Therefore, near the peak, the observed FWHM is dominated by the resolution function shape. However, the shapes of the resolution function and the RBW differ far away from the pole position. Starting (1.5–2.0) MeV from the pole position, and continuing to (5–10) MeV away (depending on the D^0 decay channel), the RBW tails are much larger. The observed event rates in this region are strongly dominated by the intrinsic linewidth of the signal, not the signal resolution function or the background rate. We use the very different resolution and RBW shapes, combined with the good signal-to-background rate far from the peak, to measure Γ precisely [10].

This analysis is based on a data set corresponding to an integrated luminosity of approximately 477 fb^{-1} recorded at, and 40 MeV below, the $\Upsilon(4S)$ resonance [11]. The data were collected with the *BABAR* detector at the PEP-II asymmetric energy e^+e^- collider, located at the SLAC National Accelerator Laboratory. The *BABAR* detector is described in detail elsewhere [12,13]; we summarize the relevant features below. The momenta of charged particles are measured with a combination of a cylindrical drift chamber and a five-layer silicon vertex tracker (SVT), both operating within the 1.5 T magnetic field of a superconducting solenoid. Information from a ring-imaging Cherenkov detector is combined with specific ionization (dE/dx) measurements from the SVT and the cylindrical drift chamber to identify charged kaon and pion candidates. Electrons are identified, and photons measured, with a CsI(Tl) electromagnetic calorimeter. The return yoke of

the superconducting coil is instrumented with tracking chambers for the identification of muons.

We remove a large amount of combinatorial and B meson decay background by requiring D^{*+} mesons produced in $e^+e^- \rightarrow c\bar{c}$ reactions to exhibit an e^+e^- center-of-mass-frame momentum greater than 3.6 GeV. The entire decay chain is fit using a kinematic fitter with geometric constraints at the production and decay vertex of the D^0 and the additional constraint that the D^{*+} laboratory momentum points back to the luminous region of the event. The pion from D^{*+} decay is referred to as the “slow pion” (denoted π_s^+) because of the limited phase space available in the D^{*+} decay. The selection criteria are chosen to provide a large signal-to-background ratio (S/B), in order to increase the sensitivity to the long signal (RBW) tails in the Δm distribution; they are not optimized for statistical significance. The criteria are briefly mentioned here and presented in detail in the archival reference for this analysis [10]. The resolution in Δm is dominated by the resolution of the π_s^+ momentum, especially the uncertainty of its direction due to Coulomb multiple scattering. We implement criteria to select well-measured pions. We define our acceptance angle to exclude the very-forward region of the detector, where track momenta are not accurately reconstructed, as determined using an independent sample of reconstructed $K_S^0 \rightarrow \pi^- \pi^+$ decays. The K_S^0 reconstructed mass is observed to vary as a function of the polar angle θ of the K_S^0 momentum measured in the laboratory frame with respect to the electron beam axis. To remove contributions from the very-forward region of the detector we reject events with any D^{*+} daughter track for which $\cos\theta > 0.89$; this criterion reduces the final samples by approximately 10%.

Our fitting procedure involves two steps. In the first step we model the finite detector resolution associated with track reconstruction by fitting the Δm distribution for correctly reconstructed MC events using a sum of three Gaussians and a function to describe the non-Gaussian component [10]. These simulated D^{*+} decays are generated with $\Gamma = 0.1$ keV, so that the observed spread of the MC distribution can be attributed to event reconstruction. The non-Gaussian function describes π_s^+ decays in flight to a μ , for which coordinates from both the π and μ segments are used in track reconstruction.

The second step uses the resolution shape parameters from the first step and convolves the Gaussian components with a RBW function to fit the measured Δm distribution in data. The RBW function is defined by

$$\frac{d\Gamma(m)}{dm} = \frac{m\Gamma_{D^*D\pi}(m)m_0\Gamma}{(m_0^2 - m^2)^2 + [m_0\Gamma_{\text{total}}(m)]^2}, \quad (1)$$

where $\Gamma_{D^*D\pi}$ is the partial width to $D^0 \pi_s^+$, m is the $D^0 \pi_s^+$ invariant mass, m_0 is the invariant mass at the pole, $\Gamma_{\text{total}}(m)$ is the total D^{*+} decay width, and Γ is the natural linewidth we wish to measure. The partial width is defined by

$$\Gamma_{D^*D\pi}(m) = \Gamma \left(\frac{\mathcal{F}_{D\pi}^\ell(p_0)}{\mathcal{F}_{D\pi}^\ell(p)} \right)^2 \left(\frac{p}{p_0} \right)^{2\ell+1} \left(\frac{m_0}{m} \right). \quad (2)$$

Here, $\ell = 1$, $\mathcal{F}_{D\pi}^{\ell=1}(p) = \sqrt{1 + r^2 p^2}$ is a Blatt-Weisskopf form factor for a vector particle with radius parameter r and daughter momentum p , and the subscript zero denotes a quantity measured at the mass pole m_0 [14,15]. We use the value $r = 1.6 \text{ GeV}^{-1}$ from Ref. [16]. For the purpose of fitting the Δm distribution, we obtain $d\Gamma(\Delta m)/d\Delta m$ from Eqs. (1) and (2) through the substitution $m = m(D^0) + \Delta m$, where $m(D^0)$ is the nominal D^0 mass [17].

As in the CLEO analysis [8], we approximate the total D^{*+} decay width $\Gamma_{\text{total}}(m) \approx \Gamma_{D^*D\pi}(m)$, ignoring the electromagnetic contribution from $D^{*+} \rightarrow D^+ \gamma$. This approximation has a negligible effect on the extracted values, as it appears only in the denominator of the RBW function.

To allow for differences between MC simulation and data, the root-mean-square deviation of each Gaussian component of the resolution function is allowed to scale in the fit process by the common factor $(1 + \epsilon)$. Events that contribute to the non-Gaussian component have a well-understood origin (π_s decay in flight), which is accurately reproduced by MC simulation. In the fit to data, the non-Gaussian function has a fixed shape and relative fraction, and is not convolved with the RBW. The relative contribution of the non-Gaussian function is small ($\leq 0.5\%$ of the signal), and the results from fits to validation signal-MC samples are unbiased without convolving this term. The background is described by a phase-space model of continuum background near the kinematic threshold [10]. We fit the Δm distribution from the kinematic threshold to $\Delta m = 0.1665 \text{ GeV}$ using a binned maximum likelihood fit and an interval width of 50 keV.

In the initial fits to data, we observed a strong dependence of Δm_0 on the slow pion momentum. This dependence, which originates in the modeling of the magnetic field map and the material in the beam pipe and SVT, is not replicated in the simulation. Previous *BABAR* analyses have observed similar effects, for example, the measurement of the Λ_c^+ mass [18]. In that analysis the material model of the SVT was altered in an attempt to correct for the energy loss and the underrepresented small-angle multiple scattering (due to nuclear Coulomb scattering). However, the momentum dependence of the reconstructed Λ_c^+ mass could be removed only by adding an unphysical amount of material to the SVT. In this analysis we use a different approach to correct the observed momentum dependence and adjust track momenta after reconstruction.

We use a sample of $K_S^0 \rightarrow \pi^+ \pi^-$ events from $D^{*+} \rightarrow D^0 \pi_s^+$ decays, where $D^0 \rightarrow K_S^0 \pi^+ \pi^-$, and require that the K_S^0 daughter pions satisfy the same tracking criteria as the π_s^+ candidates for the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ signal modes. The K_S^0 decay vertex is required to lie inside the beam pipe and to be well separated from the D^0 vertex. These selection criteria yield an extremely clean K_S^0

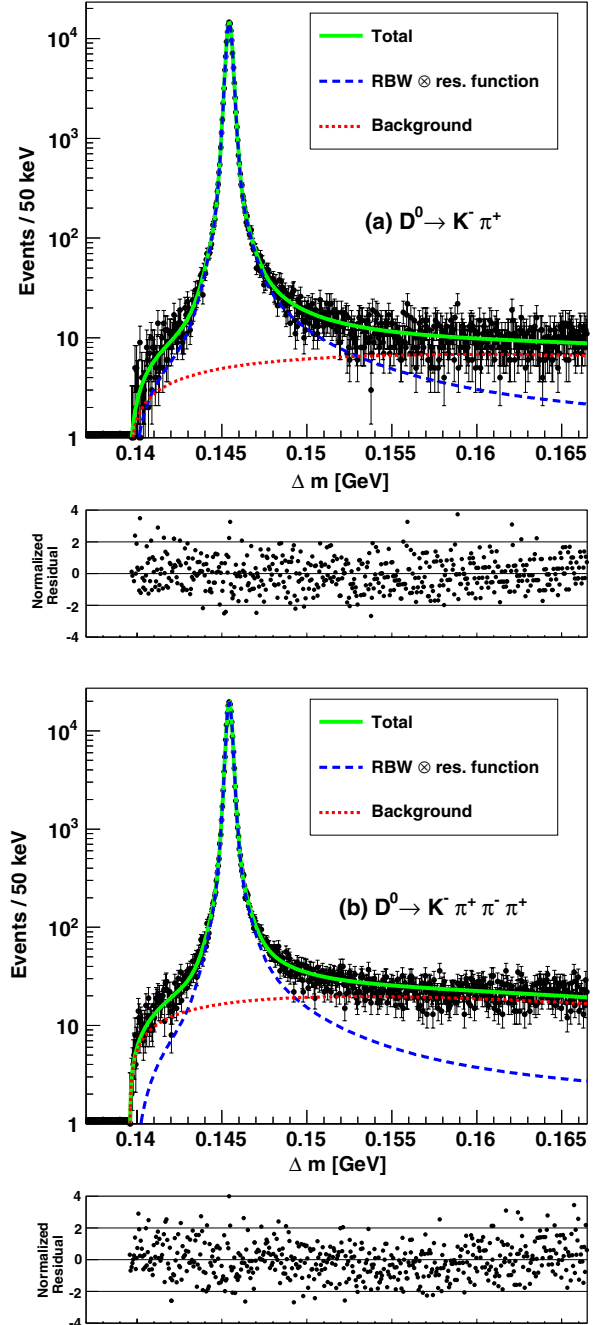


FIG. 1 (color online). Fits to data for the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decay modes. The total probability density function (PDF) is shown as the solid curve, the convolved RBW-Gaussian signal as the dashed curve, and the background as the dotted curve. The total PDF and signal component are indistinguishable in the peak region. Normalized residuals are defined as $(N_{\text{observed}} - N_{\text{predicted}})/\sqrt{N_{\text{predicted}}}$.

sample (over 99.5% pure), which is used to determine three fractional corrections to the overall magnetic field and to the energy losses in the beam pipe and, separately, in the SVT. We determine the best set of correction parameters by minimizing the difference between the $\pi^+ \pi^-$ invariant

TABLE I. Summary of the results from the fits to data for the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ channels (statistical uncertainties only). S/B is the ratio of the convolved signal PDF to the background PDF at the given Δm and ν is the number of degrees of freedom.

Parameter	$D^0 \rightarrow K \pi$	$D^0 \rightarrow K \pi \pi \pi$
Number of signal events	$138\,536 \pm 383$	$174\,297 \pm 434$
$\Gamma(\text{keV})$	83.3 ± 1.7	83.2 ± 1.5
Scale factor, $(1 + \epsilon)$	1.06 ± 0.01	1.08 ± 0.01
$\Delta m_0(\text{keV})$	$145\,425.6 \pm 0.6$	$145\,426.6 \pm 0.5$
S/B at peak [$\Delta m = 0.14542(\text{GeV})$]	2700	1130
S/B at tail [$\Delta m = 0.1554(\text{GeV})$]	0.8	0.3
χ^2/ν	574/535	556/535

mass and the current world average for the K^0 mass (497.614 ± 0.024 MeV) [17] in 20 intervals of laboratory momentum in the range 0.0 to 2.0 GeV. The best-fit parameters increase the magnitude of the magnetic field by 4.5 G and increase the energy loss in the beam pipe and SVT by 1.8% and 5.9%, respectively [10]. The momentum dependence of Δm_0 in the preliminary results was mostly due to the slow pion. However, the correction is applied to all D^{*+} daughter tracks. All fits to data described in this analysis are performed using masses and Δm values calculated using corrected momenta. Simulated events do not require correction because the same field and material models used to propagate tracks are used for their reconstruction.

Figure 1 presents the results of the fits to data for both the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decay modes. The normalized residuals show good agreement between the data and our fits. Table I summarizes the results of the fits to data for both D^0 decay modes. Table I also shows the

S/B at the peak and in the high Δm tail of each distribution.

We estimate systematic uncertainties related to a variety of sources. The data are divided into disjoint subsets corresponding to intervals of D^{*+} laboratory momentum, D^{*+} laboratory azimuthal angle ϕ , and reconstructed D^0 mass, in order to search for variations larger than those expected from statistical fluctuations. These are evaluated using a method similar to the Particle Data Group scale factor [10,17]. The corrections to the overall momentum scale and dE/dx loss in detector material are varied to account for the uncertainty on the K_S^0 mass. To estimate the uncertainty in the Blatt-Weisskopf radius we model the D^{*+} as a pointlike particle. We vary the parameters of the resolution function according to the covariance matrix reported by the fit to estimate systematic uncertainty of the resolution shape. We vary the end point used in the fit, which affects whether events are assigned to the signal or to the background component. This variation allows us to evaluate a systematic uncertainty associated with the background parametrization; within this systematic uncertainty, the residual plots shown in Fig. 1 are consistent with being entirely flat. Additionally, we vary the description of the background distribution near threshold. We fit MC validation samples to estimate systematic uncertainties associated with possible biases. Finally, we use additional MC validation studies to estimate possible systematic uncertainties due to radiative effects. All these uncertainties are estimated independently for the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ modes, as discussed in detail in Ref. [10] and summarized in Table II.

The largest systematic uncertainty arises from an observed sinusoidal dependence for Δm_0 on ϕ . Variations with the same signs and phases are seen for the reconstructed D^0 mass in both $D^0 \rightarrow K^- \pi^+$, $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$, and for the K_S^0 mass. An extended investigation revealed

TABLE II. Summary of systematic uncertainties with correlation ρ between the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ modes. The $K^- \pi^+$ and $K^- \pi^+ \pi^- \pi^+$ invariant masses are denoted by $m(D_{\text{reco}}^0)$.

Source	$\sigma_{\text{syst}}(\Gamma) (\text{keV})$		ρ	$\sigma_{\text{syst}}(\Delta m_0) (\text{keV})$		ρ
	$K \pi$	$K \pi \pi \pi$		$K \pi$	$K \pi \pi \pi$	
Disjoint D^{*+} momentum variation	0.88	0.98	0.47	0.16	0.11	0.28
Disjoint $m(D_{\text{reco}}^0)$ variation	0.00	1.53	0.56	0.00	0.00	0.22
Disjoint azimuthal variation	0.62	0.92	-0.04	1.50	1.68	0.84
Magnetic field and material model	0.29	0.18	0.98	0.75	0.81	0.99
Blatt-Weisskopf radius	0.04	0.04	0.99	0.00	0.00	1.00
Variation of resolution shape parameters	0.41	0.37	0.00	0.17	0.16	0.00
Δm fit range	0.83	0.38	-0.42	0.08	0.04	0.35
Background shape near threshold	0.10	0.33	1.00	0.00	0.00	0.00
Interval width for fit	0.00	0.05	0.99	0.00	0.00	0.00
Bias from validation	0.00	1.50	0.00	0.00	0.00	0.00
Radiative effects	0.25	0.11	0.00	0.00	0.00	0.00
Total	1.5	2.6		1.7	1.9	

TABLE III. Updated coupling constant values using the latest width measurements. Ratios are taken from Ref. [20].

State	Width (Γ)	$R = \Gamma/\hat{g}^2$ (model)	\hat{g}
$D^*(2010)^+$	$83.3 \pm 1.3 \pm 1.4$ keV	143 keV	0.76 ± 0.01
$D_1(2420)^0$	$31.4 \pm 0.5 \pm 1.3$ MeV	16 MeV	1.40 ± 0.03
$D_2^*(2460)^0$	$50.5 \pm 0.6 \pm 0.7$ MeV	38 MeV	1.15 ± 0.01

that at least part of this dependence originates from small errors in the magnetic field from the map used in track reconstruction [10]. The important aspect for this analysis is that the average value is unbiased by the variation in ϕ , which we verified using the reconstructed K_S^0 mass value. The width does not display a ϕ dependence, but each mode is assigned a small uncertainty because some deviations from uniformity are observed. The lack of a systematic variation of Γ with respect to ϕ is notable because Δm_0 shows a clear dependence such that the results from the $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ samples are highly correlated and shift together. We fit the Δm_0 values with a sinusoidal function and take half of the amplitude as the estimate of the uncertainty.

The results for the two independent D^0 decay modes agree within their uncertainties. The dominant systematic uncertainty on the RBW pole position comes from the variation in ϕ (1.5–1.9 keV). For the decay mode $D^0 \rightarrow K^- \pi^+$ we find $\Gamma = (83.4 \pm 1.7 \pm 1.5)$ keV and $\Delta m_0 = (145425.6 \pm 0.6 \pm 1.8)$ keV, while for the decay mode $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ we find $\Gamma = (83.2 \pm 1.5 \pm 2.6)$ keV and $\Delta m_0 = (145426.6 \pm 0.5 \pm 2.0)$ keV. Accounting for correlations, we obtain the combined measurement values $\Gamma = (83.3 \pm 1.2 \pm 1.4)$ keV and $\Delta m_0 = (145425.9 \pm 0.4 \pm 1.7)$ keV.

Using the relationship between the width and the coupling constant [10], we can determine the experimental value of $g_{D^{*+}D^0\pi^+}$. Using Γ and the masses from Ref. [17] we determine the experimental coupling $g_{D^{*+}D^0\pi^+}^{\text{expt}} = 16.92 \pm 0.13 \pm 0.14$, where we have ignored the electromagnetic contribution from $D^{*+} \rightarrow D^+ \gamma$. The universal coupling is directly related to $g_{D^*D\pi}$ by $\hat{g} = g_{D^{*+}D^0\pi^+} f_\pi / (2\sqrt{m_{D^0}m_{D^{*+}}})$. This parametrization is different from that used by CLEO [8]; it is chosen to match a common convention in the context of chiral perturbation theory, as in Refs. [4,19]. With this relation and $f_\pi = 130.41$ MeV, we find $\hat{g}^{\text{expt}} = 0.570 \pm 0.004 \pm 0.005$.

Di Piero and Eichten [20] present results in terms of R , the ratio of the width of a given state to the universal coupling constant. At the time of their publication, $\hat{g} = 0.82 \pm 0.09$ was consistent with the values from all of the modes in Ref. [20]. In 2010, the *BABAR* Collaboration published much more precise mass and width results for the $D_1(2460)^0$ and $D_2^*(2460)^0$ mesons [21]. Using these values, our measurement of Γ , and the ratios from Ref. [20], we calculate new values for the coupling

constant \hat{g} . Table III shows the updated results. We estimate the uncertainty on \hat{g} assuming $\sigma_\Gamma \ll \Gamma$. The updated widths reveal significant differences among the extracted values of \hat{g} . The order of magnitude increase in precision of the D^{*+} width measurement compared to previous studies confirms the observed inconsistency between the measured D^{*+} width and the chiral quark model calculation by Di Piero and Eichten [20].

After completing this analysis, we became aware of Rosner's prediction in 1985 that the D^{*+} natural linewidth should be 83.9 keV [22]. He calculated this assuming a single quark transition model to use P -wave $K^* \rightarrow K\pi$ decays to predict P -wave $D^* \rightarrow D\pi$ decay properties. Although he did not report an error estimate for this calculation in that work, his central value falls well within our experimental precision. Using the same procedure and current measurements, the prediction becomes (80.5 ± 0.1) keV [23]. A new lattice gauge calculation yielding $\Gamma(D^{*+}) = (76 \pm 7_{-10}^{+8})$ keV has also been reported recently [1].

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*Deceased.

[†]Present address: University of Tabuk, Tabuk 71491, Saudi Arabia.

[‡]Also at Università di Perugia, Dipartimento di Fisica, Perugia, Italy.

[§]Present address: University of Huddersfield, Huddersfield HD1 3DH, United Kingdom.

^{||}Present address: University of South Alabama, Mobile, Alabama 36688, USA.

[¶]Also at Università di Sassari, Sassari, Italy.

^{**}Present address: Universidad Técnica Federico Santa María, Valparaíso, Chile 2390123.

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